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Operational effectiveness of suicide-bomber-detector schemes: A best-case analysis

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Standoff explosives-detection technologies allow, in principle, for the detection of pedestrian suicide bombers, although such sensors are not yet sufficiently affordable and reliable to justify widespread deployment. What if they were? Assuming the availability of cheap, perfectly sensitive and specific suicide-bomber-sensing devices, we analyze the operational effectiveness of sensor-based detector schemes in reducing casualties from random suicide-bombing attacks. We model the number of casualties resulting from pedestrian suicide bombings absent intervention, the reduction in casualties from alternative interventions, given timely detection of a suicide-bombing attack, and the probability of timely detection under best-case assumptions governing the performance of suicide-bomber-detector schemes in two different urban settings. Even under such optimistic assumptions, we find that the widespread deployment of suicide-bomber detectors will not reliably result in meaningful casualty reductions. Relaxing the best-case assumptions only makes matters worse. Investment in intelligence-gathering to prevent suicide bombers before they attack seems a wiser strategy than relying on sensor-based suicide-bomber-detector schemes.

mathematical modeling | sensor detectors | suicide bombings

Since 2001 (1) (www.mfa.gov.il/mfa/terrorism-%20obstacle%20to%20peace/palestinian%20terror%20since%202000/), and hundreds of civilians and soldiers have been killed by SBs in the current Iraqi insurgency (www.guardian.co.uk/Iraq/page/0,12438,1151021,00.html). Frequent suicide bombings in Israel prompted the *Jerusalem Post* to complain that Israel's weapons-manufacturing industry had yet to develop a technological solution including a "failure to invent an early detection device" (2). Citing similar concerns, the Defense Advanced Research Projects Agency recently commissioned the National Research Council (NRC) of the National Academies to examine standoff explosives detection, in part, to determine "the ability to detect a suicide bomber before the bomber is able to reach his or her target and detonate the explosive" (3).

As detailed in the NRC's comprehensive report (3), sensors employing x-ray or electromagnetic imaging in the infrared, terahertz, millimeter, or microwave spectral range can, in principle, detect SB explosive belts from standoff distances of at least 10 m, and novel approaches based on explosive vapor-plume imaging, anomalies in a SB's local atmospheric-ion background, or distributed biological sensors have theoretical potential to contribute to SB-detector systems. However, existing SB sensors are far from perfectly sensitive or specific, and some of the more promising sensors are bulky and expensive, for example, millimeter wave detectors weigh 650 pounds and cost hundreds of thousands of dollars per machine (3). Existing technologies are insufficiently affordable and reliable for widespread deployment.

But what if they were affordable and reliable? Highly sensitive and specific SB detectors deployed in portal screening/checkpoint environments at known targets (such as passenger screening at airports or visitor screening at entrances to government buildings, military installations, or sports events such as the Super Bowl) could

certainly prove useful. However, consider random, pedestrian suicide-bombing attacks, that is, attacks by individual SBs on foot at randomly chosen restaurants, shops, or other locations lacking effective checkpoint security and otherwise distinguished only by a crowd of potential victims. What is the operational potential of even perfect SB-detector schemes to reduce casualties from attacks of the sort experienced in Israel, Iraq, and elsewhere?

In the spirit of recent systems analyses modeling bioterror attacks, preparedness, and response (4–6), we report an analysis that models the number of casualties resulting from pedestrian suicide bombings absent intervention, the reduction in casualties from alternative interventions, given timely detection of a suicide-bombing attack, and the probability of timely detection under best-case assumptions governing the performance of SB-detector schemes in two different urban settings. We focus on best-case detection scenarios for the simple reason that, if such optimistic analysis fails to demonstrate meaningful casualty reductions because of SB-detector schemes, then no analysis will (7).

Models

We consider pedestrian SB attacks in two urban environments. The "grid model" (Fig. 1A) presumes a layout of 200-m \times 200-m blocks separated by 10 m of street and 4 m of sidewalk width. A SB arrives at one of the intersections and walks at speed v along a blockface containing k shops. Absent detection, the SB attacks the first shop judged sufficiently attractive by entering and proceeding to its center before detonating. The probability that any shop is considered sufficiently attractive equals q . The target areas inside shops are modeled as circles with radius τ m. Perfectly specific covert sensors detecting with certainty any SB who passes within r m are embedded in the center of a fraction f of the intersections in the grid, and, if the SB is detected, there is sufficient time to execute an intervention with the hope of reducing casualties (see *Appendix*).

The "plaza model" (Fig. 1B) portrays a large plaza or park (e.g., the Mall in Washington, DC, or New York's Central Park). Potential circular targets with radius τ (e.g., crowd gatherings around performances, speakers, or outdoor cafes) are distributed within the plaza in accord with a spatial Poisson process. A SB arrives at a random location in the plaza (e.g., by car, motorcycle, or subway) and walks at speed v directly to the closest target located L m away. Perfectly specific covert sensors capable of detecting with certainty a SB who passes within r m are deployed in nonoverlapping fashion with density γ m⁻². Unlike the grid model, detection in the plaza model does not guarantee sufficient time to intervene, but the probability of timely detection [meaning at least 10 sec remain postdetection before the bomber explodes (3)] can be computed as a function of γ , r , and the expected SB travel distance, $E(L)$ (see *Appendix*).

Individuals within a target area are modeled as cylinders with height $h = 2h_0$ m and base width b m and are distributed over the

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Abbreviation: SB, suicide bomber.

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explosion equals 120 sec but grows to 0.63 as the mean time to explosion reaches 240 sec. Timely detection in the plaza model is more difficult. Although the timely detection probability grows quickly as the mean SB time to explosion approaches 20 sec, this probability quickly flattens for larger SB travel times and asymptotes to the sensor-deployment fraction f , which, in the plaza model, is the fraction of the plaza in which a SB would be detected for a given sensor density (see *Appendix*). If $f = 1$ (meaning sensors can detect SBs anywhere in the plaza), the timely detection probability equals 76% when the mean SB travel time equals 30 sec, 86% at 60 sec, 93% at 120 sec, and asymptotes to 100%. Note that, for any fixed set of parameter values, the probability of timely detection is always higher in the grid model than in the plaza model. Fig. 3*B* shows a plot of the sensor-deployment fractions required in the grid and plaza models to achieve desired timely detection probabilities. For example, to ensure that 80% of SBs are detected with at least 10 sec remaining until explosion, when SBs average 60 sec between arrival and explosion, requires deploying sensors in 79.7% of the intersections in the grid model. The requisite sensor-deployment fraction in the plaza model for the same scenario is 92.6%, which translates to a physical sensor density of $6 \times 10^{-4} \text{ m}^{-2}$. In a $500 \times 500\text{-m}$ plaza, this would equate to deploying 150 sensors.

Expected Casualty Reductions

The expected reduction in casualties that can be anticipated from best-case SB-detector schemes can be found by combining the results of the previous two sections for any scenario desired. For example, employing our base-case parameters in the grid model and assuming hit-the-deck intervention, timely detection is assured, and the expected reduction in casualties equals 19.7. The same scenario in the plaza model results in preventing an expected 16.9 casualties per attack. With $f = 0.5$, the expected number of casualties prevented would fall to 9.9 and 8.5 in the grid and plaza models, respectively. If a bomb contains, essentially, an infinite number of fragments, but, by fleeing the target area, the population density is reduced from π^{-1} to $0.5\pi^{-1}$ (so the expected target population is halved from 100 to 50), then, in the base case, the overall expected numbers of casualties averted equal 7.3 and 6.3 in the grid and plaza models, respectively. Reducing f from 1 to 0.5 would result in preventing only 3.7 and 3.2 casualties, respectively.

Discussion

Although existing and potential technologies for standoff explosives detection promise the feasibility of SB-detector schemes, even perfect detection does not necessarily translate to substantial reductions in expected casualties from random pedestrian SB attacks. To detect upwards of 80% of all attacks in a timely fashion with perfect sensors requires deployment fractions of 70–80%, depending on the relevant urban topology (grid vs. plaza, Fig. 3*B*), whereas to translate detection into a meaningful reduction in casualties requires quick implementation of interventions that, although reducing harm in certain situations, could actually lead to more casualties in others (Fig. 2).

We have arrived at these conclusions having made several best-case assumptions, including (i) perfect sensor specificity (i.e., no costly false-positive errors), (ii) perfect sensor sensitivity within the detection radius r , (iii) covert sensor placement, (iv) SB detection is always timely within the grid model, and (v) nonoverlapping sensor placement to maximize detection in the plaza model. Relaxing any of these assumptions can only lower the operational effectiveness of SB-detector schemes in reducing attack casualties.

Some might argue that the deployment of SB sensors has value, provided that such devices are *perceived* as effective: Terrorists might be deterred from attempting suicide bombings if they believe they will be interdicted, and the public might be reassured that they are being protected. However, SBs have demonstrated, on numerous occasions, their willingness to attack overtly defended targets. Both this fact and the frequency of random pedestrian suicide

bombings that are the subject of this article make the deterrence argument difficult to accept. England's experiment with widely deployed visible cameras in public places to deter crime and reassure citizens failed on both counts (www.homeoffice.gov.uk/rds/pdfs05/hors292.pdf). Moreover, the occurrence of suicide bombings against a backdrop of promised sensor-based detection and protection could rapidly transform an assured public into one of deep distrust.

Rather than focusing on technology that enables detecting SBs and last-second intervention, consider Israel's intelligence-driven approach to controlling SBs, where the great majority of planned SB attacks has been preempted by arresting would-be bombers or destroying bomb-making laboratories before an attack can be launched (1) (www1.idf.il/SIP_STORAGE/DOVER/files/6/31646.doc). Pedestrian suicide bombings might be better prevented by investing in intelligence leading to actions that *prevent* terrorists from prosecuting such attacks.

Conclusion

We have presented the formulation and results of a suite of models that, to our knowledge, is the first designed specifically to evaluate the operational effectiveness of SB-detector schemes in urban settings. Our modeling approach could also be applied to interdiction scenarios, such as the hot pursuit of terror suspects, perimeter security, or the protection of highly valuable targets (e.g., the president). Under best-case assumptions favoring the probability of timely detection over a wide range of scenarios, our results suggest strongly that even the widespread deployment of such sensors would not reliably reduce expected casualties. Although we believe that SB sensors could play a very important role in the defense of known targets, we believe our results show decisively that deploying SB-detector schemes is not likely to prove effective in protecting civilian populations from random pedestrian SB attacks.

Appendix

Casualties in an Undetected Suicide-Bombing Attack. A SB reaches the center of a circular target area with radius τ . Individuals are distributed over the target area in accord with a spatial Poisson process with a density of λ persons per unit area, resulting in an expected $\lambda 2\pi\Delta x$ targeted individuals between distances x and $x + \Delta x$ from the explosion and an expected total target population of $\lambda\pi\tau^2$ at the time of attack.

All targeted individuals are modeled as cylinders of height $h = 2h_0$ and base width b , and the SB wears an explosive belt around his waist centered at height h_0 . We make the complete-blocking assumption (8–10) that, if the line of sight between the center of a targeted individual at distance x and the center of the bomber is obscured by at least one other person, then the individual at distance x is not harmed (because all effective fragments that could potentially injure the person at distance x are absorbed by others in the way). Clearly, less-than-complete blocking would result in more casualties (8). From the spatial Poisson assumption, the probability that there are *no* individuals centered within a corridor of width b and distance x from the bomber is equal to $\exp(-\lambda bx)$; this is the probability that an individual at distance x from the SB is exposed to the explosion.

The explosion releases an expected n effective (i.e., harmful) fragments that fly in a beam spray uniformly around the bomber and uniformly over the angular dispersion $(-\beta/2, \beta/2)$, as measured from the horizontal at height h_0 . As detailed in ref. 8, the resulting density $\sigma(x)$ of effective bomb fragments per unit area in the beam spray at distance x from the explosion equals $n/(4\pi^2\sin(\beta/2))$, because the potential surface area within which effective fragments can fly at distance x equals $4\pi x^2\sin(\beta/2)$. The exposed (to bomb fragments) height $h(x)$ of a targeted individual at distance x from the explosion is equal to $2x\tan(\beta/2)$, providing $x \leq h_0/\tan(\beta/2)$, because the beam spray from an explosion at height h_0 with angular dispersion between $-\beta/2$ and $\beta/2$ can cover only heights

between $h_0 - x \tan(\beta/2)$ and $h_0 + x \tan(\beta/2)$; otherwise $h(x) = h$. The expected number of fragments capable of striking a targeted individual at distance x from the explosion thus equals $\sigma(x)bh(x)$. We assume that the distribution of the number of fragments over any fixed area of exposure also follows a spatial Poisson process (as is consistent with the uniformity assumptions governing the dispersal of bomb fragments), thus, the probability that an individual at the end of an unobstructed corridor of width b and distance x from the explosion would be hit (and harmed) by at least one effective fragment is equal to $1 - \exp(-\sigma(x)bh(x))$.

The expected number of casualties among those located at distance x from the explosion is, thus, the product of three terms: the expected number of persons located at distance x from the explosion, the probability a person at distance x is exposed to the explosion, and the conditional probability of being hit by a bomb fragment, given exposure. Integrating over all possible distances within the target area yields the expected number of casualties from the explosion, \bar{c} , as

$$\bar{c} = \int_0^\tau \lambda 2\pi x \times e^{-\lambda b x} \times (1 - e^{-\sigma(x)bh(x)}) dx. \quad [1]$$

Note that, as the number of effective fragments $n \rightarrow \infty$, the fragment density $\sigma(x) \rightarrow \infty$ as well, yielding the limiting number of casualties

$$\bar{c}_\infty = \int_0^\tau \lambda 2\pi x \times e^{-\lambda b x} dx = \frac{2\pi}{\lambda b^2} (1 - (1 + \lambda b \tau)e^{-\lambda b \tau}). \quad [2]$$

Eqs. 1 and 2 were used to produce Fig. 2A.

Reduced Casualties Because of Timely Interventions. Given timely detection [meaning at least a 10-sec warning before the bomber explodes (3)], interventions that either prevent an explosion with probability θ or fail to have any effect will save an expected $\Delta\bar{c} = \theta\bar{c}$ casualties; attempted bomber neutralization is one such intervention with θ being the probability of successful neutralization.

We model the situation where individuals in the target area are instructed to flee as equivalent to reducing the population density from λ to $\lambda' < \lambda$, which enables the use of Eqs. 1 and 2 to evaluate the change in expected casualties. Note that, because of the loss of crowd-blocking associated with reducing the population density in the target area, it is possible that “successful” implementation of this policy could, in fact, cause casualties to increase (Fig. 2A).

We also consider hit-the-deck interventions, whereby those in the target area reduce their heights from h to $h' < h$ by attempting to fall to the ground, and we optimistically assume they maintain their base width b . Assuming that the bomb still explodes at height h_0 , as before, first consider the situation if targeted individuals reduce their heights to $h' \leq h_0$. In this case, by using straightforward geometrical arguments similar to those in ref. 8, it is easy to deduce that no person located at distance $x < (h_0 - h')/\tan(\beta/2)$ would be injured in the explosion because such persons would fall completely beneath the beam spray of harmful fragments. Persons at the end of an unobstructed corridor of width b and distance $x \in ((h_0 - h')/\tan(\beta/2), h_0/\tan(\beta/2))$ from the explosion would have $h'(x) = h' - (h_0 - x \tan(\beta/2))$ of their height exposed to harmful fragments, whereas those at the end of an unobstructed corridor at distance $x \geq h_0/\tan(\beta/2)$ would have their full postintervention height exposed [i.e., $h'(x) = h'$]. Again, optimistically assuming complete blocking, an individual at distance $x > (h_0 - h')/\tan(\beta/2)$ from the explosion would be exposed to harmful fragments only if nobody is in the corridor of width b from distance $(h_0 - h')/\tan(\beta/2)$ to x [any person closer than distance $(h_0 - h')/\tan(\beta/2)$ falls beneath the beam spray and cannot contribute to crowd-blocking]; thus, the exposure probability for an individual at such a distance equals $\exp(-\lambda b(x - (h_0 - h')/\tan(\beta/2)))$. Collecting these

results (and following the logic used to derive Eq. 1), we obtain the expected casualties \bar{c}' under hit-the-deck as

$$\bar{c}' = \int_{(h_0 - h')/\tan(\beta/2)}^\tau \lambda 2\pi x \times e^{-\lambda b(x - (h_0 - h')/\tan(\beta/2))} \times (1 - e^{-\sigma(x)bh'(x)}) dx. \quad [3]$$

The expected number of casualties prevented is then given by $\Delta\bar{c} = \bar{c} - \bar{c}'$ for this case. A similar set of arguments applies to the case where the postintervention height h' falls between h_0 and $2h_0$. Eq. 3 for $h' \leq h_0$ (and its equivalent for $h_0 < h' \leq 2h_0$) was used in Fig. 2B. Note that, depending on the number of effective fragments in the explosion, hit-the-deck could increase rather than decrease the number of casualties. As was the case with reducing the population density in the target area, this possibility derives from reduced crowd-blocking.

Probability of Timely Detection: Grid Model. We presume a grid (Fig. 1A) of 200×200 -m blocks separated by 10 m of street and 4 m of sidewalk width. Each blockface contains $k = 10$ shops with entrances centered along their 20-m storefronts. A SB is dropped off at a randomly selected intersection within the grid and begins walking along one of the blockfaces. Note that the first shop entrance is located 10 m from the SB's dropoff point. Absent detection, the SB decides to attack the first shop where there are a sufficient number of individuals inside. The probability that the SB judges any given shop to be target-worthy equals q . Letting S index the shop targeted by the SB along his travel path, the probability that $S = s$ (i.e., that the SB will target the s th shop encountered) equals $q(1 - q)^{s-1}$. Note that the expected index of the targeted shop is given by $E(S) = 1/q$. The target area inside each shop is modeled in a circular fashion with radius $\tau = 10$ m; thus, the SB must walk an additional 10 m from the entrance to the center of the target area in the targeted shop. The total trip length L that an undetected SB travels before exploding is, thus, given by

$$L = \underbrace{10}_{\text{Distance to 1st shop}} + \underbrace{20(S - 1)}_{\text{Total intershop distance}} + \underbrace{10}_{\text{Intrashop distance}} = 20S, \quad [4]$$

which yields an expected trip length from arrival to explosion of $E(L) = 20/q$.

The number of individuals within a targeted shop is assumed to be distributed in accord with a spatial Poisson process with density λ per unit area, thus an undetected SB explosion results in \bar{c} casualties, as derived in Eqs. 1 and 2. However, covert sensor-based detectors capable of perfectly sensing the SB within $r = 10$ m (the required effective standoff distance for detecting pedestrian SBs) (3) are randomly located in the center of a fraction f of the intersections in the grid. Thus, if the SB is dropped off or passes through an intersection where such a detector is deployed, he will be detected with certainty, clearly a best-case assumption. Also, because experts have judged that 10 sec are required preexplosion to intervene in a suicide bombing and the typical walking speed $v = 1$ m/sec (3), our assumptions further imply that any SB detected before exploding is detected in sufficient time to intervene because, from Eq. 4, the total travel distance $L \geq 20$ m, which yields a warning of at least 20 sec, given detection (another best-case assumption). We also assume that the sensor detectors are perfectly specific, meaning that there are no false-positive SB alarms, a further best-case assumption.

Under these assumptions, the probability that a SB is detected before explosion can be reduced to the conditional probability that a bomber is detected at the beginning of a particular blockface, given that the bomber either is detected or explodes

on this same blockface. The probability of detection upon entering a blockface is simply given by f , whereas the probability that the SB explodes in a shop on a given blockface is equal to $(1 - f) \times (1 - (1 - q)^k)$, which is the probability of *not* being detected *and* selecting one of the k shops on the blockface as a target. Thus, the probability of timely detection before explosion in the grid model, p_{grid} , is given by

$$p_{\text{grid}} = \frac{f}{f + (1 - f)(1 - (1 - q)^k)}. \quad [5]$$

Eq. 5 was used in Fig. 3A.

Probability of Timely Detection: Plaza Model. We presume a large plaza or park with the centers of potential targets distributed in accord with a spatial Poisson process, with target density δ per unit area, where, again, we model targets as circular areas with radius τ and population density λ . A SB arrives at a random point in the plaza and proceeds directly toward the closest target. Given that targets are spatially Poisson-distributed, the trip length L to the closest target follows the Rayleigh distribution given by

$$\Pr\{L > \ell\} = e^{-\frac{\pi}{4}\left(\frac{\ell}{E(L)}\right)^2} \quad \text{for } \ell > 0, \quad [6]$$

where the mean trip length $E(L) = 1/(2\sqrt{\delta})$ (11). Expected casualties because of an undetected SB are, again, estimated according to Eqs. 1 and 2. Perfectly specific covert sensor detectors are distributed throughout the plaza. As in the grid model, each sensor can perfectly detect any SB who passes within the $r = 10$ m detection radius. A SB will be detected upon arrival if a sensor is located within the arrival detection zone with area πr^2 centered about the point of arrival (Fig. 1B). Barring detection upon arrival, a SB who travels distance L to the nearest target will be detected if a sensor is located within the en route detection zone of area $2rL$ centered along the direct path from the arrival point to the center of the target area (Fig. 1B). Nonoverlapping sensor deployment is assumed, which means that, at most, one sensor can be found in the union of the arrival and en route detection zones for *any* travel path; this is a best-case assumption because it maximizes the detection probability. Specifically, if there are m sensors distributed over the plaza of area a , resulting in a sensor density of $\gamma = m/a$ sensors per unit area, we assume that the probability a SB is detected upon arrival equals $m \times \pi r^2 / a = \gamma \pi r^2$ and the probability a SB is detected en route equals $m \times 2rE(L) / a = 2\gamma E(L)$. To ensure physical plausibility, the total detection zone accounting for all sensors, $m \times (\pi r^2 + 2rE(L))$, cannot exceed the area of the plaza a . This implies that

$$\gamma < \frac{1}{\pi r^2 + 2rE(L)}. \quad [7]$$

To maintain scale comparability to the grid model, we define the sensor-deployment fraction $f = \gamma \times (\pi r^2 + 2rE(L))$. The sensor-deployment fraction varies between 0 and 1 and reports the fraction of maximal coverage achieved for a given sensor deployment in the plaza model, just as f denotes the fraction of intersections covered in the grid model.

Unlike the grid model, however, detection in the plaza model does not guarantee sufficient time for intervention. Again, assuming that 10 sec are required to execute an intervention and that the

SB walks at $v = 1$ m/sec (3), the conditional probability of timely detection, given detection upon arrival, is given by

$$\Pr\{\text{timely detection} | \text{detection on arrival}\} \\ = \Pr\{L > 10\} = e^{-\frac{25\pi}{E(L)^2}} \quad [8]$$

from Eq. 6. If the SB is detected en route, nonoverlapping sensor deployment implies detection at a random location along his travel path. This means that the probability density of the *remaining* distance to the target will follow the well known residual life density of renewal theory given by $\Pr\{L > \ell\}/E(L)$ (12), and the probability that the SB will travel *at least* 10 sec postdetection before exploding equals

$$\Pr\{\text{timely detection} | \text{en route detection}\} \\ = \int_{10}^{\infty} \frac{e^{-\frac{\pi}{4}\left(\frac{\ell}{E(L)}\right)^2}}{E(L)} d\ell = 2\bar{\Phi}\left(\frac{5\sqrt{2\pi}}{E(L)}\right), \quad [9]$$

where $\bar{\Phi}(\cdot)$ is the tail probability associated with the standard normal distribution. Combining our results, the unconditional probability of timely detection p_{plaza} , which is the probability that at least 10 sec remain until explosion postdetection in the plaza model, is given by

$$p_{\text{plaza}} = \gamma \pi r^2 \times e^{-\frac{25\pi}{E(L)^2}} + 2\gamma r E(L) \times 2\bar{\Phi}\left(\frac{5\sqrt{2\pi}}{E(L)}\right). \quad [10]$$

Eq. 10 was used in Fig. 3A.

Minimum Sensor Deployment. Let p_i denote the probability of timely detection in scenario $i = \text{grid, plaza}$. The sensor-deployment fraction $f_i(\alpha)$ required for timely detection with probability α in scenario i must force $p_i = \alpha$. For the grid model, this implies, according to Eq. 5, that the fraction of intersections covered by sensors is equal to at least

$$f_{\text{grid}}(\alpha) = \frac{\alpha - \alpha(1 - q)^k}{1 - \alpha(1 - q)^k}. \quad [11]$$

For the plaza model, the corresponding minimal sensor-deployment fraction is equal to

$$f_{\text{plaza}}(\alpha) = \alpha \times \frac{\pi r^2 + 2rE(L)}{\pi r^2 \times e^{-\frac{25\pi}{E(L)^2}} + 2rE(L) \times 2\bar{\Phi}\left(\frac{5\sqrt{2\pi}}{E(L)}\right)}, \quad [12]$$

as follows from Eq. 10, and the definition of the sensor-deployment fraction follows Eq. 7. Eqs. 11 and 12 were used to produce Fig. 3B.

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